Structural Health Monitoring Technologies and Next-Generation Smart Composite Structures

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Development of Embedded FBG Sensor Networks for SHM Systems

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INTRODUCTION

Fiber-reinforced polymer (FRP) composites being an engineering material for many decades. The main attraction of the FRP is its superior strength-to-weight ratio. In particular, aircraft and defense industries have been spending billions of dollars on investment in these composites to produce lightweight subsonic and supersonic aircrafts. Other desirable properties, such as the ease of fabrication of complex shapes and the ability to tailor desirable properties to suit different engineering applications, are enviable for an advanced material. Research and development work in past few
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decades FRP composites has made inroads to delicate aerospace and space industries. Therefore the use of FRP Composite in aerospace industry has been increased by a significant amount in recent years.

The weight-save or positive weight spiral in the aircraft industry is directly translated to the enhancement of the load carrying capacity of civil aircraft, whereas for the fighter jets, it will be translated to the performance enhancement (mainly on the fuel carrying capacity versus the flying speed). As composites are partially made from polymer-based materials, they possess very good damping and fatigue resistance properties as compared with traditional metallic materials.

The commercial aircraft industry is gradually replacing metallic parts with FRP composites as much as possible. Hence, the FRP composites are frequently applied to primary load-bearing structures in the newly developed aircraft such as Boeing 787 and Airbus A380. However, the main disadvantages of using FRP composites in the aircraft industry are their difficulty for repair, anisotropic behavior, high initial setup cost, and most importantly the complex failure criteria. Because of these undesirable properties, the FRP composite structures in the aircraft need to be closely monitored to prevent unexpected failure.

Aircraft structures have numerous stress-concentrated regions such as pin-loaded holes and other cut-outs. These stress concentrations easily induce damages such as concurrent splitting, transverse cracking, and delamination (Chang and Chang, 1987; Kortscho and Beaumont, 1990; Kamiya and Sekine, 1996). Unlike metals, the damage accumulation and the damage prediction of composites are very difficult to predict and can be catastrophic. Because of this reason, it is essential to monitor advance composites structures such as expensive aerospace structures regularly. As a consequence, structural health monitoring (SHM) technique has recently been developed for FRP composite structures majorly for aerospace structures (Zhou and Sim, 2002; Chang, 2003). During past few decades monitoring of structural health of composites began with damage detection techniques such as vibration and damping methods (Adams et al., 1978). Then sophisticated and expensive offline nondestructive testing (NDT) methods were developed for the safe operation of composite structures. However, with the increasing complexity of structures, offline NDT was criticized as insufficient and developments of proper SHM systems became vital.

There are many procedures and technologies need to be integrated to form intelligent SHM systems. The indicator for damage, one of the most important parameter of an SHM, is defined as changes to the material properties or changes to the structural response of the structure. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors. The SHM system developed to monitor aircraft and space structures must be capable of identifying multiple failure criteria of FRP composites (Reveley et al., 2010). Since the behavior of composites is anisotropic, multiple numbers of sensors must be in service to monitor these structures under multidirectional complex loading conditions. The layered structure of the composites makes it difficult to predict the structural behavior only by using surface sensors.

An SHM system must be efficient, robust and accurate to detect complex and hidden the process of damage propagation (Reveley et al., 2010). Because of recent
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developments in the aerospace industry, utilization of FRP composites for primary aircraft structures, such as wing leading-edge surfaces and fuselage sections, has increased leading to a rapid growth in the field of SHM. Various causes such as impact, vibration, and loading can initiate damages, such as delamination and matrix cracking, to FRP composite structures. Moreover, the internal material damage can be undetectable using conventional techniques, making inspection of the structures for damage and clear insight into the structural integrity difficult using currently available evaluation methods.

Since the behavior of composites is anisotropic, multiple numbers of sensors must be in service to monitor these structures under multidirectional complex loading conditions. The layered structure of the composites makes it difficult to predict the structural behavior only by using surface sensors.

Many modern light aircraft are being increasingly designed to contain as much lightweight composite material as possible. For elevated-temperature applications carbon-fiber-reinforced composite is in use. Concord’s disk brakes used this material, rocket nozzles and re-entry shields have been fashioned from it, and there are other possibilities for its use as static components in jet engines. Rocket motor casings and rocket launchers are also frequently made of reinforced plastics. A particularly interesting (and important) application of composites is in its development in Australia as a means of repairing battle damage (patching) in metal aircraft structures.

Space applications offer many opportunities for employing light-weight, high-rigidity structures for structural purposes. Many of the requirements are the same as those for aeronautical structures, since there is a need to have low weight and high stiffness to minimize loads and avoid the occurrence of buckling frequencies. Dimensional stability is at a premium, for stable antennae and optical platforms, for example, and materials need to be transparent to radio-frequency waves and stable toward both UV radiation and moisture. Progressive damage in laminated composite can be subdivided into two:

1. Micromechanics (matrix-fiber)
2. Macromechanics (lamina)

The evolution of a matrix crack as the initial stage of damage, followed by delamination, is also true for composites subjected to impact load (Marshall et al., 1985). In most of the damage models reported in literature are transverse matrix cracks, splitting, and delamination. The degradation of effective elastic module of damaged laminates used as the damage parameters. The observed damage parameters by online health monitoring, such parameters can further be interpreted to damage states. The final stage of damage progression identified as “Delamination,” which is the failure of the interface between two plies, is known as the silent killer of the composite structures. It is caused by normal and shear tractions acting on the interface, which may be attributed to transverse loading, free edge effect, ply-drop-off, or local load introduction. Delamination can significantly reduce the structural stiffness and the load carrying capacity and, therefore, is considered as one of the critical failure modes in laminated composites.
SHM SYSTEMS FOR FRP COMPOSITES

The process of implementing a damage detection and characterization strategy for engineering structures is referred to as SHM. The SHM process involves the observation of a system over time using periodically sampled structural response measurements from an array of sensors. Most of offline NDT methods do not fall into SHM.

With the complex failure modes of FRP composites, the need for SHM of composite structures becomes critical. With the recent developments in the advanced composite applications, utilization of FRP composites for primary aircraft structures, such as wing leading-edge surfaces and fuselage sections, has increased. This is one of the major reasons for the rapid growth in the research fields related to SHM. Impact from flying objects, excessive vibration, and loading can cause damage such as delamination and matrix cracking to the FRP composite structures. Moreover, the internal material damage in the FRP composite structures can be invisible to the human eyes. In some cases, delaminations and cracks remain closed while the structure is under no loaded condition. As a consequence, inspection for damage and clear insight into the structural integrity become difficult using currently available evaluation methods.

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DEVELOPMENT OF FBG SENSORS FOR SHM SYSTEMS

The SHM system developed to monitor FRP composite structures must be capable of identifying the multiple failure criteria of composites (Reveley et al., 2010). Since the behavior of most composites is anisotropic, multiple numbers of sensors must be in service to monitor these structures under multidirectional complex loading conditions. The layered structure of the composites makes it difficult to predict the structural behavior by using surface mounted sensors only. To address this issue embedded sensors need to be used, and these sensors must be robust enough to service the structure’s lifetime. It is impossible to replace embedded sensors after fabrication of the parts.

In particular, the fiber Bragg grating (FBG) sensor is one of the most suitable sensors for the SHM of aircraft FRP structures. The FBG sensors can be embedded into FRP composites during the manufacture of the composite part with no adverse effect...
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on the strength of the part as the sensor is diminutive in size. Furthermore, this sensor is suitable for networking as it has a narrowband response with wide wavelength operating range, hence can be highly multiplexed. As it is a nonconductive sensor it can also operate in electromagnetically noisy environments without any interference. The FBG sensor is made up of glass which is environmentally more stable and with a long lifetime similar to that of FRP composites. Because of its low transmission loss, the sensor signal can be monitored from longer distances making it suitable for remote sensing (Kersey et al., 1997; Hill and Meltz, 1997).

The FBGs’ capability of detecting stress gradients along its grating length can be used to identify the stress variations in the FRP composites by means of chirp in the reflected spectra of the FBG sensor (Hill and Eggleton, 1994; Le Blanc et al., 1994). This phenomenon can be used to detect damage in the composite structures (Okabe et al., 2000; Takeda et al., 2002). But, it has been reported that the chirp of the FBG spectrum is not only due to stress concentrations caused by damage accumulation in the composite structure (Wang et al., 2008). There are other reasons for chirping of spectra and eliminating such effects during the processing of spectra is necessary to identify damage accurately. The most recent development in the fiber optic sensor field is the pulse-pre-pump Brillouin optical time domain analysis (PPP-BOTDA) (Che-Hsien et al., 2008). The PPP-BOTDA is capable of achieving a 1 cm spatial resolution for strain measurements and the resolution is further improving. The PPP-BOTDA-based system has been successfully used in various industrial applications; however, PPP-BOTDA is so far only able to measure the static or quasistatic strain and soon will be developed for dynamic readings.

FIBER BRAGG GRATINGS

FBGs are formed by constructing periodic changes in the index of refraction in the core of a single mode optical fiber. This periodic change in index of refraction is typically created by exposing the fiber core to an intense interference pattern of UV radiation. The formation of permanent grating structures in optical fiber was first demonstrated by Hill and Meltz in 1978 at the Canadian Communications Research Centre (CRC) in Ottawa, Ontario, Canada. In ground breaking work, they launched high-intensity argon-ion laser radiation into germanium doped fiber and observed an increase in reflected light intensity. After exposing the fiber for a period of time it was found that the reflected light had a particular frequency. Subsequent spectral measurements were taken, and these measurements have confirmed that a permanent narrowband Bragg Grating filter had been created in the area of exposure.

The Bragg grating is named after William Lawrence Bragg who formulated the conditions for X-ray diffraction (Bragg’s law). These concepts, which won him the Nobel Prize in 1915, related energy spectra to reflection spacing. In the case of FBGs, the Bragg condition is satisfied by the above-mentioned area of the modulated index of refraction in two possible ways based on the Grating’s structure. The first is the Bragg reflection grating, which is used as a narrow optical filter or reflector. The second is the Bragg diffraction grating which is used in wavelength division multiplexing and demultiplexing of communication signals.
The gratings first written at CRC, initially referred to as “Hill gratings,” were actually a result of research on the nonlinear properties of germanium-doped silica fiber. It established, at the time, a previously unknown photosensitivity of germanium-doped optical fiber, which led to further studies resulting in the formation of gratings, Bragg reflection, and an understanding of its dependence on the wavelength of the light used to form the gratings. Studies of the day suggested a two-photon process, with the grating strength increasing as a square of the light intensity (Lam and Garside, 1981). At this early stage, gratings were not written from the “side” (external to the fiber) as commonly practiced now, but were written by creating a standing wave of radiation (visible) interference within the fiber core introduced from the fiber’s end.

After their appearance in late 1970s, the FBG sensors had been using for SHM of composite materials efficiently for more than two decades. Recent advances in FBG sensor technologies have provided great opportunities to develop more sophisticated in situ SHM systems. There have been a large number of research efforts on the health monitoring of composite structures using FBG sensors. The ability to embed them inside FRP material between different layers provides a better opportunity to receive valuable data inside the structure. The attractive properties such as small size, immunity to electromagnetic fields, and multiplexing ability are some of the advantages of FBG sensors. The lifetime of an FBG sensor is well above the lifetime of the FRP structures and also it provides the measuring of multiple parameters such as load/strain, vibration, and temperature (Kashyap, 1999).

In 1989, Meltz et al. showed that it was possible to write gratings from outside the fiber. This proved to be a significant achievement as it made possible future low-cost manufacturing methods of Bragg Gratings and enabled continuous writing or “writing-on-the-fly.” With this method of writing gratings, it was discovered that a grating made to reflect any wavelength of light could be created by illuminating the fiber through the side of the cladding with two beams of coherent UV light. By using this method (holography), the interference pattern (and, therefore, the wavelength of reflected light from the grating) could be controlled by the angle between the two beams, something not possible with the internal writing method, as seen in Figure 3.1. The figure shows two methods of manufacturing a side-written grating. Figure 3.1b shows the light beam incident to the fiber with a phase mask. In Figure 3.1a, the two coherent beams of light form an interference pattern which creates a standing wave with variable intensity of light. The variable radiation intensity occurs within the fiber core. This variation in radiation intensity creates a modulated index of refraction profile within the fiber core. In Figure 3.1b, the modulation is created by using a single light beam and a phase mask. In areas where the mask allows light transmission, the index of refraction is changed within the core, creating the grating. This technique is particularly useful to write gratings quickly. Both of these methods allowed for “tuning” of the grating to whatever wavelength was desired. This, in itself was an important development, as it allowed gratings to be easily written at various wavelengths to follow the communications industry’s changing source wavelengths. In addition, it was found at the time that this method was far more efficient.

The first method of fabricating gratings was internal writing through standing waves of radiation and the second method was the holographic side writing of gratings. Consequently, both of these methods have been surpassed by the use of the
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The phase mask (Anderson et al., 1993; Hill et al., 1993). The phase mask is a planar slide of silica glass or similar structure which is transparent to UV light. A periodic structure with the appropriate periodicity is etched onto the glass slide to approximate a square wave using photolithography (as viewed from the side). As shown in Figure 3.2, use of phase mask for fabrication of grating in use of the phase mask for fabrication of gratings, the optical fiber is placed very close to the phase mask while the grating is written. UV light is introduced to the fiber and is diffracted by the periodic structure of the phase mask, creating the grating structure described above. The periodic structure created in the fiber is half that of the spacing of the periodic structure in the phase mask. In this manufacturing technique, the periodicity of the FBG is independent of the wavelength of the UV light source. The wavelength of the UV light source is selected based on the absorbance spectra of the doped optical fiber core, thereby maximizing the source’s efficiency in writing gratings. Use of

FIGURE 3.1  (a) Split beam interferometer and (b) phase mask technique.

FIGURE 3.2  Use of phase mask for fabrication of grating.
phase masks made lower cost, and made greater precision Bragg gratings possible by simplifying the manufacturing process. In addition, the phase mask technique made it possible to automate grating writing, and to write multiple gratings on a fiber simultaneously. The phase mask procedure allowed for the efficient writing of other types of gratings such as chirped gratings which have nonconstant periodicities for a wider spectral response.

The process of writing a grating using the phase mask method is illustrated in Figure 3.3. Figure 3.3a and b show the setup for the grating writing process with the phase mask and mirror arrangements to direct the laser to the phase mask and the phase mask mounted just above the fiber, respectively. Figure 3.3c shows the writing in progress and Figure 3.3d shows the corresponding response from the created grating.

The reference spectrum shown in Figure 3.3d was used to maintain the consistent reflection power of the sensors. When the reflected spectrum from the grating reached the reference spectrum power, the writing process was terminated. Excessive exposure of the fiber to the laser will broaden the reflection spectra as shown in Figure 3.4, which makes it hard to track the peak of the spectrum.

The side lobes are one of the major drawbacks of using phase mask technique for FBG fabrication. As shown in Figure 3.5, side lobes of an FBG sensor response spectrum are inherent to a particular phase mask and will be written to all FBG sensors fabricated using that phase mask. “Apodization” technique can be used to get rid of those side lobes, but it will extinguish the uniformity of the grating length (\( \lambda \)) which drops the sensitivity of the sensor for SHM purposes.

FIGURE 3.3 Fabrication of FBG sensor using phase mask method (a) setup for the writing, (b) phase mask, (c) writing in progress, and (d) response of the grating.
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**Principle of Bragg Grating**

As described previously, FBG sensors are fabricated in the core region of specially fabricated single mode low-loss germanium doped silicate optical fibers. The grating is the laser-inscribed region which has a periodically varying refractive index. This region reflects only a narrow band of light corresponding to the Bragg wavelength \( \lambda_B \), which is related to the grating period \( \Lambda_0 \):

\[
\lambda_B = \frac{2 n_0 \Lambda_0}{k}
\]  

(3.1)

where:

- \( k \) is the order of the grating
- \( n_0 \) is the initial refractive index of the core material prior to any applied strain

**FIGURE 3.4** Broadening of the reflection spectra due to over exposure to laser light.

**FIGURE 3.5** Side lobes of an FBG sensor response spectrum.
Because of the applied strain, $\varepsilon$, there is a change in the wavelength, $\Delta\lambda_B$, for the isothermal condition,

$$\frac{\Delta\lambda_B}{\lambda_B} = \varepsilon P_e$$  \hspace{1cm} (3.2)

where $P_e$ is the strain optic coefficient and is calculated as 0.793.

The Bragg wavelength is also changing with the reflective index. Any physical change in the fiber profile will cause variation of the reflective index. The variation of the Bragg wave length $\lambda_B$, as a function of change in the refractive index $\Delta\delta n$ and the grating period $\delta \Lambda_0$ is given below.

$$\delta \lambda_{\text{Bragg}} = 2\Lambda_0 \eta \delta n + 2\eta_{\text{eff}} \delta \Lambda_0$$  \hspace{1cm} (3.3)

where:
- $\eta$ is the core overlap factor of about 0.9 times the shift of the Bragg wavelength
- $\eta_{\text{eff}}$ is the mean refractive index change
- $\Lambda_0$ is the grating period

For the Gaussian fit, the sensor reflectivity can be expressed as

$$s(\lambda, \lambda_s) = y_0 + S_0 \exp\left[ -\alpha_s \left( \lambda - \lambda_s \right)^2 \right]$$  \hspace{1cm} (3.4)

where:
- $y_0$ is the added offset to represent the dark noise
- $\alpha_s$ is a parameter related to the full width at the half maximum (FWHM)
- $\lambda$ is the wavelength
- $\lambda_s$ is the central wavelength
- $S_0$ is the initial reflectivity of the fiber

A major advantage of using FRP composites is the possibility of deciding on the number of layers and layup orientation based on the required structural behavior. In an FRP composite aerospace structure there are a number of layers with multiple orientations. The layers are placed one on top of the other and hence it is possible to embed FBG sensors in any layer during the manufacturing of the structure.

**EMBEDDING FBG SENSORS IN FRP STRUCTURES**

The process of embedding FBG sensors in FRP composites is quite complicated. The level of difficulty is largely dependent on the geometry of the part, lay-up configuration and embedding location of the sensors in the part. In general, FBG sensors will be placed closer to critical sections of the structure where high stress concentrations are predicted. However, in reality, locating FBG sensors in predicted locations are not always possible. On the other hand, reliance on a single sensor is not recommended as it is not possible to replace failed embedded sensors after manufacturing.
As a result, many FBG sensors need to be embedded in the surrounding area closer to the critical locations of the structure to capture strain levels reliably.

As such, multiplexed FBG sensors play a critical role in the SHM of aerospace structures. Normally in FRP, the damage starts from stress concentrations. In the process of implementing SHM systems, identification of the locations that have potential for damage is essential. Finite element analysis techniques are being widely used to identify stress concentrations and, hence, to locate FBG sensors. It is less likely that FBG sensors are placed in simple planer structures in real applications, apart from where the requirement is mere strain rather than the damage detection.

Difficulties associated with the manufacturing of composite structures with embedded FBG sensors are the main problem with placing FBG sensors in a complicated location. The aerospace industry’s advanced manufacturing technologies, such as prepreg and autoclave process) creates hazards environments for brittle sensor. Every precaution needs to be taken to not apply loads on the sensor in the uncured resin matrix during the manufacturing process. With applied pressures as high as 700 kPa, even the egress ends of the sensors need to be supported to avoid breakage. It is essential to develop methods to protect FBG sensors during the FRP composite manufacturing processes. Since there is no way of replacing damaged FBG sensors after manufacturing of the component, a strict set of procedures must be developed to follow during manufacture.

Figure 3.6b shows a support given to the egress end of the sensor. Sometimes it is helpful to have an extra protective layer of rubber applied to the fiber to maximize the handling of samples without damage to the sensors.

**DISTORTION OF EMBEDDED FBG SENSOR SPECTRA**

FBG sensors are very good in strain measurements and the linear unidirectional sensitivity in the axial direction of the sensor is desirable for accurate and reliable strain readings. In such applications, the FBG sensor undergoes pure elongation or contraction and hence, the cross section always remains in a circular shape. In multidirectional loading cases, an FBG sensor may be subjected to torsional deformations.
other than linear elongation or contraction. For example, when a torque is applied to a composite sample which has an embedded FBG sensor, it undergoes a twist which may cause changes to its cross section.

Another possibility of changed cross section of FBG sensors under torsional loading is due to microbending of the grating. The embedded sensor is not always laid on the matrix and there is a possibility of laying an FBG between reinforced fibers. In case, if a structure is under lateral pressure, the fiber sitting on the FBG sensor will press the FBG sensor against the fibers, causing the sensor to experience microbends. These changes of the cross section of the FBG lead to changes in the refractive index of the core material of the sensor. Because the changes are not uniform along the grating length, the refractive index of the sensor unevenly varies along the grating length of the sensor causing distortion in the FBG spectra.

It is obvious that the distortion of FBG sensors depends on the type of loading. The effect of the twist and microbending of FBG sensors under multiaxial loading has been identified as the causes for this discrepancy. The change of section geometry of the FBG sensor due to microbending and twisting, leads to a variation of the refractive index of the FBG core material which causes distortion of the FBG response spectra. Figure 3.7 illustrates a distorted FBG sensor response due to tension and torsion combined loading on the FRP panel which the FBG is embedded (Kahandawa et al., 2010a, b, 2011, 2013b).

The majority of research work on FBG sensors in SHM of composite structures has focused on investigation of the spectra of FBG sensor embedded in the vicinity of damage. Observations of the distorted sensor spectra due to stress concentrations caused by delaminations and cracks have been used to estimate the damage.
conditions. Many researchers have investigated purposely damaged axially loaded specimens, and the changes of FBG spectra were attributed to the damage and successfully identified the damage (Takeda et al., 2008). In real life situations, the applied loads are not limited to uniaxial loads and hence the performance of FBGs in multiaxial loading situation needs to be investigated for a complete understanding of damage status. The FBG spectral response is significantly complicated under multiaxial loading conditions (Sorensen et al., 2007; Kahandawa et al., 2010a, 2012a). The distortion of FBG spectra is not only due to the accumulated damage, but also the loading types. In the previous section, it was shown that embedding FBGs between nonparallel fiber layers and the application of torque caused substantial distortions to the FBG spectra.

Even through the distortion of the response spectra of an FBG sensor has been widely used in SHM applications to detect structural integrity, unfortunately there is still no definite method available to quantify the distortion. This has been a significant drawback in the development of SHM systems using embedded FBG sensors for decades. Quantification of distortion of the FBG sensor will allow referencing and comparison to monitor for the progressive damage status of a structure. An explicit method to quantify distortion to the sensor including self-distortion needs to be developed.

Kahandawa et al. (2013a) has proposed a “distortion index” (DI) to quantify distortion in the FBG spectrum. The DI is calculated related to the original spectrum before the presence of any damage.

The DI is calculated related to the original spectrum before the presence of any damage (Kahandawa et al., 2013a). Distortion \( (D_x) \) is defined using the FWHM value of FBG spectra and the maximum power of the FBG response spectrum. FWHM is an expression of the extent of a function given by the difference between the two extreme values of the independent variable at which the dependent variable is equal to half of its maximum power (Figure 3.8).

Generally for an FBG response spectrum, the FWHM value increases with the distortion while the peak value decreases. \( \text{FWHM} = (x_2 - x_1) \).

\[
\text{FWHM} = \frac{-\ln(2)}{2} \]

**FIGURE 3.8** Full width at half maximum.
For the comparison, the distortion $D_s$ and the DI, need to be calculated for the same load case. Distortion of the peak at a particular load case, $D_s$, can be expressed as

$$D_s = \frac{\text{FWHM}}{P}$$  \hspace{1cm} (3.5)

where $P$ is the peak strength of the FBG sensor reflection spectra in dB as shown in Figure 3.9. With the calculated distortion value, the DI can be calculated.

DI at the same load case:

$$\text{DI} = \frac{D_{si}}{D_{s0}}$$  \hspace{1cm} (3.6)

where:

- $D_{si}$ is the current distortion
- $D_{s0}$ is the distortion at the original condition (no damage)

If the structure is undamaged, $D_{si}$ is equal to $D_{s0}$ for the same load case. In that case the DI is equal to unity. With the presence of damage, the response spectrum of an FBG sensor broadens (FWHM increases), while the peak power of the spectrum decreases. As a result $D_{si}$ increases making the DI value above unity. This phenomenon can be used to identify the presence of damage in a structure.

To verify the DI, it is better to use several load cases to calculate distortion and corresponding DIs. At the initial stage, the structure can be subjected to several known load cases, and corresponding distortion, $D_{s0}$, can be recorded. In future operations, those load cases can be used to calculate the DI to identify damage. In the following experiment, the DI has been calculated to investigate the relationship of DI to a growing defect.

![Figure 3.9](image_url)
DAMAGE PREDICTION

Previous discussions in this chapter have shown that multiple causes lead to the distortion to the FBG response spectra. Most of the intrinsic effects cause by embedded FBG sensor between parallel fiber laminates, parallel to the fiber orientation, and also multidirectional loading, could not be isolated from the spectra of FBG sensors. To identify damage from the distortions to the FBG response spectra, the individual effect from each effect needs to be identified and eliminated. To identify the pure effects from the damage, distinguished from the other effects, extensive computational power is required for postprocessing of the spectral data. Figure 3.10 shows FBG response spectra from an FBG embedded near a purposely created damage location with the part under the complex multidirectional loading.

In a laboratory condition a crack can be simulated and related FBG spectra can be obtained easily. In these purposely created experimental situations the response spectra (distortion) of embedded FBG can be explained. However, distorted response spectrum from an embedded FBG sensor is not easy to convert to exact damage condition of the structure. This incongruity made some of the SHM researchers disappointed and discouraged.

Kahandawa et al. (2012b) have proposed a novel statistical technique using artificial neural network (ANN)-based approach to handle a large data base of FBG sensor network for predict accurately the damage condition. The response of the FBG during the undamaged states of the structure is recorded, and this recorded data are used as a “reference” for the analysis. Therefore, the isolation of possible “reference” data from a distorted spectrum of any embedded FBG sensor will be possible and subsequent distortions to the spectra caused during the operational life of the structure/component.

The main difficulty for this approach is to develop a system to reference the FBG response spectra. Historically, statistical methods such as ANNs have been used to

![FIGURE 3.10 Distorted FBG spectra due to multiple effects.](https://example.com/figure3.10)
analyze such complicated data associated with a large number of random variables. The main advantage is the ability to train an ANN with undamaged data, and the trained ANN can be used to distinguish new spectral variations of FBG sensor responses. To input spectral data to the ANN, decoding system needs to be developed. To address the above issues, the “fixed FBG filter decoding system” (FFDS) was developed to capture the distortion to the FBG sensor response spectra.

**DECODING DISTORTED FBG SENSOR SPECTRA**

During the past decade, many systems for decoding FBG spectra using fixed FBG filters have been developed (Lewis et al., 2007; Nunes et al., 2007; Veiga et al., 2008; Zimmermann et al., 2008; Lopes et al., 2010). Figure 3.11 illustrates a general arrangement of a fixed FBG filter system. The system consists of a tunable laser (TLS), fixed FBG filter, optical couplers (CPs) and photo detector (PD). A high-frequency data acquisition system (DAQ) has been used to acquire the PD voltage values.

Figure 3.11 illustrates the simplest form of this system, using only one (1) FBG filter, which is the building block of the complete decoding system. TLS light, A, is transmitted to the FBG sensor and the reflected light, B, of the FBG sensor is fed to the FBG filter through an optical CP. The intersection of the wavelengths reflected from the sensor and the wavelengths’ reflected light, C, by the filter (λ), or conversely, the wavelengths which are not transmitted through the filter, are reflected to the photodetector. L₁ and L₂ are the light transmitted through the FBG sensor and filter, respectively.

![FIGURE 3.11 FBG spectrum decoding system α(t), timed response spectra.](image-url)
While the sensor receives the total wavelength range from the TLS source, the filter only receives the wavelengths reflected by the sensor. Hence, the filter can only reflect light (to the photodetector) if the wavelength from the sensor is within the filter’s grating range ($\lambda$). The reflected light of the filter is captured using the photodetector, converted to a voltage, and recorded in the DAQ system. A system can be implemented with multiple FBG filters with $\lambda_n$ wavelengths as required for a specific application.

Figure 3.12 shows the reflected spectra of the FBG sensor and the filter. The filter can only reflect light if the received wavelength from the sensor reflection is within the filter’s grating range. Thus, the filter reflects the intersection as shown in Figure 3.12.

The reflected light of the FBG filter was captured using the PD and the voltage was recorded using the DAQ. Figure 3.13 shows the PD voltage in the time domain corresponding to the intersection of the spectra shown in Figure 3.12. TLS sweeping frequency allows transformation of voltage reading to time domain. Since the filter spectrum is fixed, the intersection of the two spectra only depends on the sensor spectrum position. Variation of the intersection can be used to identify the location of the peak, the strain at sensor, and the damage status of the structure. Any distortion to the spectrum is visible from the PD voltage–time plot (Figure 3.13). By matching the TLS swept frequency with the DAQ sampling frequency, it is possible...
to transform voltages to respective wavelength values accurately. More filter readings will increase the accuracy, the operating range and robustness of the system.

There were several attempts to fit the FBG spectra using mathematical functions such as the commonly used Gaussian curve fit (Nunes et al., 2004). Sensor reflectivity can be expressed as

$$S(\lambda, \lambda_s) = y_0 + S_0 \exp \left[ -\alpha_s (\lambda - \lambda_s)^2 \right]$$  \hspace{1cm} (3.7)

where:

- $y_0$ is the added offset to represent the dark noise
- $\alpha$ is a parameter related to FWHM
- $\lambda$ is the wave length

Unfortunately Gaussian fit always gives an error for a distorted spectrum as shown in Figure 3.14a. Realistically, a distorted spectrum must be considered as a piecewise continuous function, $f_{pc}$ to capture the distortion. Consequently, optical power, $P$, of the distorted signal can be obtained using the following integral:

$$P = \beta \int_{t_a}^{t_b} f_{pc} \, dt$$  \hspace{1cm} (3.8)

where:

- $\beta$ is a constant dependent on the power of the source
- $t_a$ and $t_b$ are the integral limits in the time domain, respectively (Figure 3.14b)

The power integral at each point can be used to estimate the strain in the sensor by using an ANN. The sensitivity of the integrated data depends on the integral limits; larger integration limits reduce the sensitivity and very small limits cause data to scatter. Both cases make the algorithms inefficient. Optimum limit values have to be set to achieve better results.
DEVELOPMENT OF ANN-BASED DECISION-MAKING ALGORITHM

The SHM systems used in damage detection in FRP composites must be capable of identifying the complex failure modes of composite materials. The damage accumulation in each layer of a composite laminate is primarily dependent on the properties of the particular layer (McCartney, 1998; McCartney, 2002) and the loads which are imposed onto the layer. As such, the layered structure of the composite laminates makes it difficult to predict the structural behavior using only surface attached sensors. Over the past few years, this issue has been critically investigated by many researchers using embedded FBG sensors (Eric, 1995; Lee et al., 1999; Takeda et al., 2002, 2003, 2008).

The majority of the research works were focused on the investigation of the spectra of FBG sensors embedded in the vicinity of damage loaded with unidirectional loading. However, in real life situations, the applied loads are not limited to uniaxial loads and hence the performance of FBGs in multiaxial loading situation needs to be investigated for comprehensive damage characterization.

The FBG spectral response is significantly complicated by multiaxial loading conditions (Sorensen et al., 2007), fiber orientation, and the type of damage present in the structure (Kahandawa et al., 2010a, b). It has been shown that FBG’s embedded between nonparallel fiber layers and subjected to torque create significant distortions in the spectra (Figure 3.15).

It is clear that the cause of the distortion of FBG spectra depends, not only on the consequences of accumulated damage, but also on loading types and the fiber orientation. Embedding FBGs in between nonparallel fiber layers and the application of torsional loading to the component have caused substantial distortions to FBG spectra. To identify damage using the response of the FBG sensor, the other effects imbedded in the response needs to be identified and eliminated. The introducing referencing technique for the FBG spectrum using fixed wavelength FBG filters, provides the capability of identifying the variations to the FBG spectrum and distinguish the other effects causing distortions. Consequently, elimination of distortions caused by other effects will permit identification of distortions of FBG
spectra caused by the damage. The proposed system is used to capture the distortions of reflected spectra of an embedded FBG sensor inside a composite laminate, thus enabling a quantitative estimate of the damage size in the vicinity of the sensor.

The aforementioned effects on the FBG spectrum along with the accumulation of damage make the response of the FBG highly nonlinear. The nonlinearity of the response varies from structure to structure hence the estimation of transfer functions is extremely difficult. In this scenario, statistical methods provide promising results for data processing. Among the methods available, the ANN has provided proven results for nonlinear systems with high accuracy. Application of ANNs is an efficient method for modeling nonlinear characteristics of physical parameters and creates a system which is sensitive to wide range of noise.

The decoding of spectral data to feed in to ANN was addressed using a fixed filter FBG decoding system. The main objectives in this work are to decode the spectral data to determine the average strain at the embedded location. Furthermore, identification of damage also will be discussed. This method eliminates lengthy postprocessing of data, and bulky equipment for data acquisition (as shown in Figure 3.16).

**ANN-Based Damage Detection**

With the complex damage modes of composite materials and complex spectral responses of FBG sensors under complex operational loading, the damage detection in composite materials using FBG sensors becomes extremely difficult. Incorporation of multiple sensor readings is also a challenging task. Further, extraction of important data and the elimination of valueless data imbedded in the response spectra of an FBG is a challenging task. Even though it is possible to avoid these complications in the laboratory environment, in real applications these are not avoidable. To overcome these difficulties the introduced novel FFFDS with an ANN is being used.

The FFFDS uses the desirable characteristics of ANN to work and train with complications, to identify the real working environment. As a result of considering the working environment as the base (reference), the system’s sensitivity to changes

![A typical distortion of FBG spectra.](image)
such as damage, was remarkably improved. The following section introduces the field of ANNs and the characteristics.

**Introduction to Neural Networks**

ANNs are commonly referred as “Neural Networks” (Haykin, 1998). This concept emerged while scientists were looking for a solution to replicate human brain. In some cases like identification and prediction, the human brain tracks the problem more efficiently than other controllers. That is because the human brain computes in an entirely different way from the conventional digital computer.

The human brain is a highly complex, nonlinear and parallel computer (information processing system) (Kartalopoulos, 1995). It has the capacity to organize its structure constituents, known as neurons, so as to perform certain computation many times faster than the fastest digital computer available today.

For an example, in human vision, the human routinely accomplishes perceptual recognition tasks such as recognizing a familiar face embedded in a familiar scene in approximately 100–200 ms, whereas tasks of much lesser complexity may take hours on a conventional computer (Freeman and Skapura, 2007). Hence, we can say that the brain processes information superquickly and superaccurately. It can also be trained to recognize patterns and to identify incomplete patterns. Moreover, the trained network works efficiently even if certain neurons (inputs) failed. The attraction of ANN, as an information processing system is due to the desirable characteristics presented in the next section.

The fixed wavelength filters and data capturing system is used to decode spectral data from an FBG sensor to a form which can be fed into an ANN to estimate strain and/or damage in a composite structure.

Figure 3.17 illustrates a data flow diagram of the structural strain and damage assessment process. First, reflected spectral data from the FBG sensor mounted on the structure is entered into an FBG filter. The reflected spectral data from the FBG filter (representing the spectral intersection of the reflected FBG sensor data and
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The inherent filter characteristics) is entered into a photodetector. The voltage time domain output of the photodetector is entered into a data acquisition unit. The data are then processed and entered into a neural network. Finally, the neural network output is the state of strain and/or damage (Figure 3.18).

Figure 3.19 depicts a general arrangement of the proposed system. The system consists of a TLS, three (3) fixed FBG filters (Filters 1–3), optical CP and three (3) photodetectors (PD). A high-frequency DAQ was used to record the photodetector output voltages which are subsequently fed into the processor to determine the state of strain and damage.

Three (3) filters are used to increase the accuracy, operating range and robustness of the system, and the composite signal created by the photodetectors represents a unique signature of the sensor spectrum. Furthermore, the output of the photodetectors contains information relative to the sensor spectra in a form which can be used with an ANN. The number of filters and FBG sensors is not limited to the example shown in this figure. Any one filter in the system is capable of covering an approximate range of 500 microstrain/1 nm movement of the peak of the sensor spectrum. More filters can be used with the same system to cover a wider operating range of the embedded FBG sensors and to obtain more precise data.

**POSTPROCESSING OF FFFDS DATA USING ANN**

As discussed in Section “Distortion of Embedded FBG Sensor Spectra,” under complex load conditions, the spectrum of the FBG distorts. Figure 3.20 shows the FBG sensor response of an FBG embedded in a composite structure during operation under several load cases. The complicated response makes it extremely difficult to
model using mathematical transfer functions to estimate strain as well as damage. In such cases, an ANN provides promising functional approximations to the system.

One of the commonly used neural network architectures for function approximation is the multilayer perceptron (MLP). Backpropagation (BP) algorithms are used in a wide range of applications to design an MLP successfully (Lopes and Ribeiro, 2001).

The ANN Model

Figure 3.21 shows a general arrangement of the ANN used in this study. The ANN consists of three input neurons, which accommodate three FBG fixed filters, three hidden layers, and an output layer.
The neurons of the hidden layers are with Gaussian activation functions, and the $k$ value used is 1, as shown in Figure 3.22a. It takes a parameter that determines the center (mean) value of the function used as a desired value. The neuron of the output layer is with sigmoid activation function with $k = 1$, as shown in Figure 3.22b. This function is especially advantageous for use in neural networks trained by BP.
algorithms because it is easy to distinguish, and can minimize the computational capacity of training (Karlik and Olgac, 2010). Initial weights (at the start of the training process) of the neurons were randomly placed between $-1$ and $1$.

Three different composite specimens, with embedded FBG sensors, were investigated using the developed system to evaluate the system performance for estimation of strain and/or damage.

**CONCLUSION**

The superior performances and the unique advantages of the FBG sensors have strongly established their place for the SHM of FRP composite structures. At this stage, the success of the SHM with FBG sensors is expanded from the laboratory
environment to the real structures. However, to make this technology reliable and readily accessible, further research is warranted. The embedding technology, robustness of the sensors and FBG interrogation techniques must be critically addressed. The postprocessing of FBG spectral data needs to be developed with the recent advancements of statistical data analysis algorithms.

REFERENCES


